

The quest for quarks

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Contents

Acknowledgements vii

- 1 The structure of matter 1
 - 2 The strange particles 38
 - 3 Quarks 72
 - 4 The great accelerator hunt 97
 - 5 The quest for the free quark 111
 - 6 Matter and the Universe 144
- Index* 157

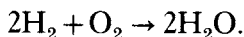
I

The structure of matter

I was born and brought up in north-eastern England. At a fairly early stage in my scientific education I became acquainted with the notion of ‘atoms’ – fundamental, indivisible particles out of which all things are made. Oddly enough, the first occasion that I can remember when the idea cropped up was my reading a newspaper story about a forthcoming attempt to ‘Split the Atom’ – to divide the indivisible.

The story was a bit scary. The reporter wondered if a successful attempt would let loose such vast energies as might wreak havoc with the world. Scientists were said to pooh-pooh the idea, and in the short run they were right. But maybe the intuitive reporter knew better in the long run. The Cockcroft–Walton experiment was part of the Cambridge research programme leading to the discovery of the neutron, that in its turn led to the fission of uranium and that to the atomic and hydrogen bombs.

Anyhow, the idea of atoms seemed to me very sensible – all these many complicated things in the Universe neatly explained as combinations of a few simple objects. It was an old (Grecian) idea made modern and scientific by John Dalton, a fellow north country man. When I began to study chemistry at school, atomism was taken as obvious by my teachers and even more so by me:



It was simple, obvious, beautiful.

I heard that only a minority of the ancient Greek philosophers were atomists and I concluded that most Greek philosophers must have been rather stupid. This was reinforced when I heard that they had such an aversion to experiment that they would

argue for days about the number of teeth a horse had rather than examine a horse. I loved experiment; chemistry and physics practical classes were the best times of my school week. There is a story that Wolfgang Pauli, in the early days of quantum mechanics, once burst in upon Heisenberg and Bohr and said 'You should read more of Einstein; he's not half as stupid as you might think!' And, of course, the Greek philosophers were not half as stupid as I thought. Thales, Anixamander, Heraclitus, Parmenides, Pythagoras, Plato, Aristotle; none of them were atomists. Democritus was very much in the minority. So, when John Dalton suggested that matter is atomic, that the material Universe is composed of just a few types of indivisible, fundamental entities, he was going against the weight of informed opinion, established over many centuries.

Dalton had a few very great men of more recent times on his side. Newton favoured atomism.

It seems probable to me, that God, in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in such Proportion to Space, as most conduced to the End for which he form'd them.

Leibniz also tried to erect a doctrine of the world based on 'physical' atoms. But though Dalton had such people of the highest quality on his side, the great weight of opinion was against him.

What drove him to revive this Grecian minority opinion? Mostly the recent (recent in AD 1805) discoveries in chemistry. These could be stated as five laws:

(1) The law of conservation of mass: in a chemical reaction the total mass of the various substances at the end of the reaction is equal to the total mass of the substances at the beginning of the reaction. This had been a difficult law to arrive at because quite often one of the components in a reaction (either before or after) is a gas and people found it difficult to weigh gases – or even, sometimes, to know that they were there. For instance, when iron rusted they did not at first know that it was taking oxygen from the atmosphere.

(2) The law of constant proportions: all pure samples of compounds contain the same elements combined in the same proportions by weight. By this time people had some idea of elements and compounds. Water, for instance, had been separated by Sir Humphry Davy (and an electric current) into hydrogen and oxygen. The hydrogen and oxygen had then been combined (by burning one in an atmosphere of the other) to form water.

(3) The law of multiple proportions: if two elements combine to form more than one compound then the several weights of A combining with a fixed weight of B are in simple ratios. Good examples of this are the oxides of nitrogen, which we would today write as N_2O , NO , N_2O_3 , NO_2 and N_2O_5 . So if we had 30 units by weight of oxygen then the amounts of nitrogen by weight in these five compounds would be in the ratios 60:30:20:15:12.

(4) The law of reciprocal proportions (sometimes called the law of equivalents): the weights of elements A, B and C that combine with a fixed weight of another element are the weights with which A, B and C will combine with each other, or simple multiples of them.

(5) Gay-Lussac's law (put forward in 1808): when gases react they do so in volumes which bear a simple ratio to each other and to the volumes of any gaseous products.

It is fairly obvious that most of these laws are nicely explained by the hypothesis that all matter is made from a fairly small number of elements and that the elements are made from atoms, the atoms of any one element being indistinguishable from one another but different to the atoms of any other element. The atoms are considered to be 'true' atoms, indivisible and indestructible.

The first law follows at once; there are just as many of the unchangeable, indestructible atoms at the end of the reaction as there were at the beginning. Laws 2, 3 and 4 are readily seen once we use the modern symbolism: H_2O for water, for instance, meaning that two atoms of hydrogen and one of oxygen give a molecule of water; H_2O_2 for hydrogen peroxide, and so on.

Gay-Lussac's law gave Dalton some trouble. He got round it, in effect, by saying that Gay-Lussac's experiments were wrong – which caused some amusement amongst the cognoscenti, for Gay-Lussac was one of the best experimentalists of the day and Dalton, definitely not so. But it was all tidied up by Avogadro when he drew the distinction between atoms and molecules and realised that elements can come in molecular form. This he did in 1811 though, very surprisingly, his work was not widely recognized till 1860 when his compatriot Cannizzaro drove the point home at a conference in Karlsruhe. By this time the conference delegates could read Cannizzaro's paper as they returned home to their various towns in Europe by steam train rather than the stage coaches of Dalton's day.

By this time, Dalton's idea was being applied in physics, particularly in what is called the kinetic theory of gases. This is the theory that explains (and predicts) the properties of gases by assuming they are made of molecules, which are in rapid, random motion, and that the kinetic energy of motion of the molecules constitutes the heat energy of the gas. This idea seems to have originated with Herapath, who supposed the atoms to be perfectly hard. It is difficult to envisage the collision of perfectly hard spheres – one feels that something has to give, but what? Waterston, who followed Herapath, chose to consider perfectly *elastic* spheres for his molecules. And of course this brought the criticism that he was explaining the elasticity of gases by assuming they were made of elastic particles; and where was the advance? However, Maxwell and Clausius put aside this objection (for the time being) and developed a mathematical theory of gases, which accounted for many properties of gases and correctly predicted others. From this time on the atomic theory was established in the scientific community. This is not to say that all scientists believed in the reality of atoms, or that they all became 'atomists' rather than 'continuists'. But the majority realised that here was a reasonable model, with considerable predictive power and scope for development. (And quite a few believed wholeheartedly in the atomic hypothesis.)

However, the need to have a perfectly elastic atom to make

the theory work *did* imply that the atom is complex, not the simple, indivisible, particle that is the fundamental building block of all matter. Another line of reasoning suggesting the same thing was the *number* of different sorts of atom needed to explain chemical activity. The ancient Greek atomists had only postulated four (or sometimes five) different sorts: earth, air, fire and water (plus, possibly, aether). But once Mendeleev had systematised his table of the chemical elements, it was clear that at least 92 different types of atom were needed in the 'modern' system. But 92 seemed a large number of allegedly 'fundamental building blocks' of nature. The atoms fell under suspicion of being complex objects. In the last decade of the 19th century this was shown indeed to be so by experiments in a fairly new field of study in physics, the conduction of electricity through gases.

The study of this phenomenon depended on two advances in technique. These were the ability to produce and maintain a 'vacuum', that is, a considerable reduction in gas pressure in a glass vessel of reasonable capacity – a litre, say – and the ability to produce moderately high electrical voltages (a few thousand volts) from a supply that would give a noticeable (if rather small) current. A sketch of the sort of apparatus used is shown in fig. 1.1. The evacuated vessel has two electrodes; that attached to the negative side of the supply is the cathode, the other is the anode. If a small hole is made in the anode one finds that some entity ('cathode rays', they were called) will travel through the hole and, if the far end of the tube is coated with a phosphor, will cause a small bright glowing spot to appear. A modern television tube is a sophisticated descendant of this simple device. It was found that these cathode rays could be deflected in a magnetic field; they acted like a stream of negative electricity (which is exactly what they are).

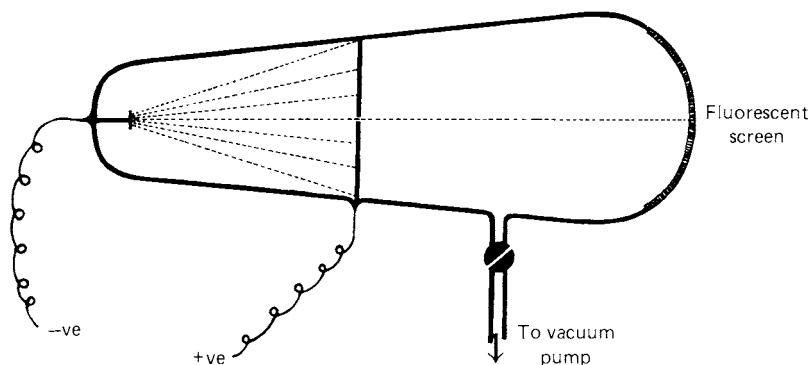
In Cambridge, J. J. Thomson (later Sir J. J. Thomson, Nobel Laureate) was able to measure the ratio e/m of their charge e to their mass m . A little later it became possible to measure the same ratio e/m for the 'positive rays' moving in the opposite direction in a tube containing a small pressure of

hydrogen gas. This ratio was about 2000 times smaller than the first ratio e/m but very close to the value obtained by a study of the electrolysis of hydrogen compounds like hydrochloric acid. Thomson drew the correct conclusion, namely that he was dealing with two constituents of the hydrogen atom, a positive particle, which accounted for most of the hydrogen mass, and a negative particle of equal and opposite charge and about 2000 times lighter than the positive particle. The negative particle was called an electron (first by Johnstone Stoney, an Irish physicist who suspected its existence from studies of electrolysis). The positive particle became known as a proton.

With this simple apparatus, which nowadays any handyman with a reasonable skill in glassblowing could make, the ‘atom’ had been split. It does not take much energy to do it; 100 electron volts is ample for one atom – that is, the energy an electron acquires when it experiences a potential drop of 100 volts. But it is a much bigger energy per atom than one comes across in the usual sort of chemical interaction.

So, from the beginning to the end of the 19th century, atoms

Fig. 1.1. A sketch of a gas discharge tube. A vacuum pump is used to remove most of the gas in the tube, which can then be sealed off with the tap. An electrical potential of a few thousand volts is then applied across the two metal electrodes – the right-hand electrode in the figure is positive. Cathode rays (electrons) then stream from left to right. If a small hole is made in the anode some of the electrons can stream through it and strike a screen of some scintillating material on the glass end of the tube. A TV tube is a sophisticated descendant of this device.



had been suggested, had been made scientifically respectable, and had been shown not to be atoms! Fortunately for the atomists, two new 'particles' had appeared, the electron and proton, which were certainly constituents of the chemical 'atoms' and might be the real fundamental building blocks of nature – the real atoms. And there were only two of them; the modern atomists were (at least temporarily) two up on their colleagues of ancient Greece.

Of course the study of the structure of matter did not stop here (otherwise there would have been no quest for quarks). The idea that matter is made up of just two sorts of particle, one a charge of positive electricity and the other a charge of negative electricity, is simple and appealing but it led to difficulties. To see what these were we need to look at two areas of physics.

The first was fairly well established in 1900. I have mentioned it already: the kinetic theory of gases. It took as its starting point the belief that all gases are made of molecules, and sought to relate the microscopic properties of these molecules, their speeds, diameters, masses and so on, to the macroscopic properties of the gas. It was (and is) very successful. The other branch of physics was quite new in 1900. It was radioactivity. Kinetic theory (as I shall show in a moment) gives us good estimates of the *sizes* of atoms and molecules. Radioactivity shows that, if atoms are the size claimed by the kinetic theory, then most of their volume is 'empty space' and the greater part of their mass is concentrated in a very much smaller volume – just as the greater part of the mass of the Solar System is concentrated in the Sun. From this stems a whole variety of ideas about matter.

The idea redeeming Dalton's theory was Avogadro's hypothesis and the distinction he made between an atom and a molecule. Avogadro realised that two similar atoms, for example two atoms of hydrogen, might combine to form a molecule of hydrogen and that this is the stable form of hydrogen under the conditions holding at the Earth's surface. (In interstellar space things are different. There the usual form of hydrogen is atomic hydrogen.) Avogadro's hypothesis was that equal volumes of

gases (at the same temperature and pressure) contain the same number of molecules. The hypothesis is now so well confirmed by experiment that it is often called Avogadro's law. From this law we see that the masses of two equal volumes of different gases are in the ratio of their molecular masses. Chemists quickly realised the usefulness of this in calculations. For any substance, the amount of it that weighs in grams the same as its molecular weight always contains the same number of molecules. They called this amount a gramme-mole. They (and the physicists) found a variety of ways of counting the number of molecules in this amount of matter. This number is now called Avogadro's number.

One of the ways, which is easy to explain, relied on electrolysis — the break up of a compound when an electric current is passed through it. When some substances, such as hydrochloric acid (HCl), are dissolved in water they dissociate. The molecules of HCl dissociate into positive hydrogen ions (an ion is an electrically-charged atom or molecule) and negative chlorine ions. If we dip two electrodes into such a solution and maintain one positive and the other negative, then the positive ions are attracted to the negative electrode (or cathode) and neutralised. They then grab the nearest other neutral hydrogen atom and form a hydrogen molecule. Lots of molecules unite to form a bubble of hydrogen gas, which rises to the surface and can be collected. We need, of course, to supply electricity constantly to keep the cathode negatively charged. We can meter the amount of electricity supplied and so find out how much electricity (that is, what amount of electric charge) is needed to liberate a grm-mole. The smallest unit of electric charge has been measured in various ways — the first successful experiment was carried out by the American physicist R. A. Millikan — and so the number of molecules in a grm-mole became known. It is big, 6.023×10^{23} .

Now a grm-mole of hydrogen gas can occupy a large volume. This volume depends on the temperature and pressure. The gas is usually easy to compress, so one guesses there is a good deal of space between the molecules. But when the hydrogen is

liquefied it is difficult to compress any further, so the molecules must be almost touching. By dividing the volume of a gram-mole of liquefied hydrogen by 6.023×10^{23} one gets the volume of one molecule of hydrogen (to a close approximation). From this one gets an idea of its linear dimensions. Most atoms turn out to have radii of about 10^{-10} metres. Once the volume of a molecule is known its cross-sectional area becomes calculable. Then, if the number of molecules in a given volume is known, it is easy to calculate the mean distance a molecule will travel between collisions, which is called its mean free path. Again, by measuring the amount of heat it takes to bring a gram-mole of gas from close to the absolute zero of temperature (-273°C) up to, say, 15°C , one measures the amount of energy in the gram-mole and hence gets the mean kinetic energy of a molecule at 15°C (or any other temperature one chooses). The kinetic energy is given by $\frac{1}{2}mV^2$ where m is the mass of the molecule and V its velocity, and so we get an idea of the speed at which the gas molecules are flying around in the atmosphere. At 15°C it is about 0.5 km/sec, 1800 km/hr – well over the speed limit! So, by a few quite simple experiments we have found out the number of molecules in a given amount of matter, their size, their mass, and their mean velocities at room temperature.

Now for the other half of the study – radioactivity. In a way, this came out of the study of the conduction of electricity through gases that I spoke of earlier. Röntgen, in 1895, had found that when cathode rays hit a solid object, the glass of the tube for instance, they give off an invisible radiation, which he called X-rays. These X-rays, as you know, can penetrate solid matter and blacken photographic emulsion even when it is in a light-proof packet. Following up this discovery when it was the talk of the world, Becquerel in France discovered that a sealed box of photographic plates was blackened when placed next to a uranium salt. He drew the correct conclusion: the uranium was giving off rays, like X-rays. Radioactivity had been discovered. Both Röntgen and Becquerel were awarded Nobel Prizes for their discoveries. The amazing phenomenon of radioactivity was soon the subject of many investigations. It was

spontaneous: a piece of uranium (or thorium) did not need any electric or magnetic field to produce these radiations. They just poured out of it.

Radioactivity stirred the imagination of many people other than professional scientists. In 1905 H. G. Wells wrote a science fiction novel in which he forecast the use of 'atomic bombs'. It is very interesting to compare that prediction, forty years before the atomic attack on Hiroshima, with Lord Rutherford's remark in 1936 that 'anyone who talks of energy from the atom is talking moonshine'. The intuition of the artist is often much more effective in prediction than the detailed knowledge of the 'scientist'.

But Rutherford was a superb experimental investigator in the early days of radioactivity and attracted some very talented physicists from many countries to his laboratories, first in Canada, then Manchester, and then Cambridge. He was one of the people who sorted out the three types of radiation coming from radioactive materials. These were first, α -particles, which turned out to be the nuclei of helium atoms, four times as heavy as protons and with twice their positive electric charge; secondly, β -particles, which turned out to be high speed electrons; and thirdly, γ -radiation, which was like X-radiation but more penetrating than any X-radiation one could generate in those days.

Rutherford found that he could use the α -particles from radium as a kind of probe. He fired these α -particles (whose energy was around 5 million electron volts, written, 5 meV) at thin gold foils. Many of the particles went straight through without noticeable deflection, a few were deflected slightly, and very occasionally one was deflected through a large angle. Now the cause of the deflection seemed almost certain to be the electric charges in the atom. The law of force between two electric charges, q_1 and q_2 , is simple:

$$\text{force} = Kq_1q_2/r^2,$$

where K is a constant, which depends on what units of measurement we use and r is the distance between the charges. But if the charge on the atom is spread out over a radius of

10^{-10} m (small as that is) this force is nothing like strong enough to deflect the fast, heavy, α -particles noticeably. Rutherford said that to see these α -particles bouncing back from the gold foil (as they very occasionally did) was as surprising to him as firing a 15-inch shell at a sheet of paper and having it bounce back. For the α -particles to behave in this way the positive charge in the gold atoms must be concentrated in a region about 100 000 times smaller in radius than the whole atom, that is, within a radius of about 10^{-15} m. The idea of the nuclear atom had appeared!

Rutherford pictured the atom as something like a miniature solar system with the tiny, heavy, positively-charged nucleus at the centre, as the Sun is at the centre, and the electrons revolving round it. But this model had its problems. First, the matter in the nucleus must be exceedingly dense, much more dense than lead, in fact about 4×10^{13} times denser! Then there was the odd fact that the nucleus of helium is four times heavier than a proton and had only two positive charges. It looked as if the helium nucleus is made of four protons *and* two electrons. But the helium atom still had its two electrons 'in orbit'. Why should some electrons go into the nucleus and others go into orbit? And the orbital electrons had their difficulties. An electron moving in a circle is being accelerated – its direction of motion is constantly being changed from the straight line that it would follow if no external forces were acting on it. It is just the same for the Earth, of course. Our direction of motion is constantly being changed by the gravitational pull of the Sun. But when an electric charge is accelerated, it radiates energy as electromagnetic radiation, light, radio waves, or X-rays, depending on the energy. In any case it radiates energy, which is to say, it loses energy; it slows down and this makes it spiral in towards the central positive charge. Moreover, with such small distances as we have in the atom, this should happen very quickly – in about 10^{-12} s, a million millionth of a second. So, according to the physics of the day (about 1912), such an atom was not even approximately stable.

Fortunately, at this time, there was a young Danish physicist

of genius working in Rutherford's laboratories in Manchester – Nils Bohr. He was aware of the fairly new quantum theory and promptly applied it to this 'planetary' model of the atom. He 'quantised' the orbits of the electron, supposing only certain orbits are allowed. This made the atomic 'planetary' system very different to our Solar System. Moreover, he supposed that when an electron was in one of these orbits it did not lose energy (for some unknown reason). It only lost energy when it jumped (again, in some unknown way) from one orbit to another. This model would not have been accepted if all it did was to explain Rutherford's scattering experiment. But it did much more. With it Bohr was able for the first time to calculate the wavelengths of the light emitted by hydrogen atoms and so to explain the spectrum of hydrogen. He could also make quite a reasonable shot at the spectra of some other elements. This was a spectacular advance.

You will notice that Bohr had to put up with a lot of uncertainty to get his model. He could not say (at this point) why the electrons in stationary orbits did not radiate, or why the nuclear matter was so dense, or what happened when the electron made a jump and so on. He had not by any means got a complete theory of the atom. But he had got a theory that was much better than anything else around. You might also notice another thing. Trying to find the truth about the detailed structure of matter is like trying to catch a well-oiled eel in a darkened aquarium with, maybe, the thought in your mind that there is possibly a piranha or two in the tank.

To come back to the Bohr model of the atom: the study of the fine structure of matter, the search for the fundamental building blocks of the Universe, divides at this point. The two paths seem to go off in different directions, but discoveries on each path have been essential to the study of the other. And later on the paths in a sense rejoin one another. One path is the study of the electrons; the other, of the nucleus.

The first and most obvious difference between them is one of scale. In the Bohr model the nucleus is *very* small, 10^{-15} m in radius, is very dense, having almost all the mass of the atom

in it, and is positively charged. The electrons are spread out over a much larger volume (100 000 times the radius of the nuclear radius, so 10^{15} times the volume), are quite light particles, and are negatively charged. It was the study of these particles and the outer sections of the atom they occupy that first led to great advances. Almost literally, the nucleus was a tougher nut to crack.

To see what went on in the outer atom we need to backtrack a little to the end of the 19th and beginning of the 20th century. In an address to the British Institution at the turn of the century, Lord Kelvin, a great Scots theoretical physicist, said that physics in the 19th century had made spectacular progress. It was in extremely good shape. Only two small clouds marred the sunny blue sky and he expected these would soon disappear. One was the odd result of Michelson and Morley's experiments on the velocity of light: it appeared to be unaffected by the motion of the Earth around the Sun, contrary to the forecasts of physics. The other was the failure of theoretical physics to account for the way energy radiating from a hot black body varies with wavelength. Now I am sure a lot of people would find the first of these a rather esoteric detail to worry about, and the second one almost ludicrously so. It says a lot for Lord Kelvin's intuition that unerringly he had spotted two major defects in the physics of his day. But his reasoning was not as good as his intuition; these two clouds did not fade away. The first led Einstein to his theories of relativity, to $E = mc^2$ and so on. The second, which is the one that concerns us now, led Max Planck to his quantum theory.

Until Max Planck, physicists had assumed that when energy was transferred from one body to another it could be transferred *continuously*, in arbitrarily small amounts. Planck decided to try the opposite idea, that it could only be transferred in 'packets' of a definite size. He decided that if he were considering electromagnetic radiation of a definite frequency ν (nu, the Greek ν), then the size of the energy packet was $h\nu$, where h is a fundamental constant that is now called Planck's constant. In a way this was applying the atomic hypothesis to energy

transfer. But there was a difference. As long as we stick to frequency ν , then the size of the packet is $h\nu$. But we can always take another frequency, change ν and so change $h\nu$. We can always, for example, move from bluish-green light to greenish-blue light. But once we fix ν , we just cannot make energy transfers of $\frac{1}{3}h\nu$, or $\frac{11}{5}h\nu$ – it has to be done in units of $h\nu$. It is a bit like currency. If you are paying in bank notes you can only pay in, say, units of \$1. The value of the dollar against gold may be sliding up and down from day to day, but you can only pay in these units.

With this apparently simple modification Planck was able to derive a theoretical ‘energy against wavelength’ curve that accurately matched the experimental result. And Planck knew that the apparently simple modification was of a very fundamental nature. In fact it led to the overthrow of Newtonian physics and to changes in our ideas about the Universe that are certainly still going on and may well have only just begun.

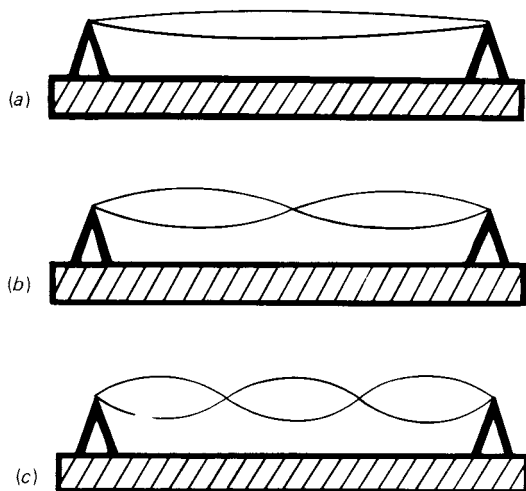
One of the first people to appreciate the importance of Planck’s step was Einstein. In 1905 he used it to explain the photo-electric effect. It had been found that when some metals are illuminated they emit electrons. Some details of this process were quite puzzling until Einstein used the idea that the light energy is delivered to the metal in these ‘packets’. The idea explained the formerly puzzling aspects; Einstein was awarded the Nobel Prize principally for this work rather than for his theory of relativity. It was, indeed, a big step. It showed physicists that light, which for nearly a century they had known to be wave-like, behaved, when it interacted with matter, more like a stream of tiny birdshot. Light, in fact, had a dual nature. It diffracted, refracted and interfered like waves do; but when it interacted with, say, a photographic film, it behaved like a stream of particles. These particles were soon called photons.

At first sight this duality seemed impossible. For physicists, particles and waves were a good deal more different than chalk and cheese. Both ideas, of course, were abstractions from reality. But wave motion was thought of as a non-local phenomenon. A system of plane waves is easiest to deal with if thought of as

stretching to infinity both forward and back and from side to side – and also as having no beginning or end. A particle, on the other hand, is precisely located. The particle is thought of as a speck of matter; the wave is a wave in some medium. For light, the medium was at first called the aether; later, light was thought of as a wave motion in the electromagnetic ‘field’. In practice, a billiard ball is a good approximation to a particle – as is a planet, considered as part of the Solar System. The easiest waves to visualise are probably waves on the surface of a pond or the ocean. The two, particle and wave, are the antithesis of each other, but this new theory was saying that light is *both* – or at least behaves like both from time to time.

Worse was to come, in the sense of more paradoxes. In Paris, in 1925, Prince Louis de Broglie thought that if a wave (like light) might display particulate behaviour, maybe a particle, like an electron, might have also a wave nature. He considered the Bohr atom as a resonating system. The simplest analogy is a guitar string. A guitar string can vibrate in various ways. Some of them are shown in fig. 1.2. Always one must have nodes at the two ends; there, the string is fixed and cannot move. If these are the only nodes then the string is vibrating in what musicians call its fundamental mode. The wavelength of the vibration is

Fig. 1.2. Three possible modes of vibration of a stretched string.



then just twice the length of the string. If we have an extra node in the middle we have the first harmonic; its wavelength is just the length of the string. Then there are higher harmonics, with shorter wavelengths. In a guitar, the string is ‘coupled’ to the guitar body, which can reinforce some of the harmonics and suppress others. Also, a good guitarist knows how to excite different harmonics by his playing and so produce different tonal qualities at will. De Broglie thought of the Bohr atom as such a system, with various possible harmonics corresponding to the radii of the supposed orbits of the electron. He found he could get the right values if he supposed that the wavelength, λ , to be associated with the electron is given by $\lambda = h/mv$, where m is the mass and v the velocity of the electron, so mv is the *momentum* of the electron. h is Planck’s constant, cropping up here once again.

This suggestion that electrons have waves associated with them was radical. But it was also quite easy to check up on. Waves produce characteristic effects – diffraction, interference, and so on. If we have a point source of light and a screen, and we interpose between them an opaque sheet with one pin hole in it, then the image we get on the screen is not just a single bright dot. Instead, it has a number of bright and dark rings around it. The experiment is just a little tricky to do because the wavelength of light is so short, but is standard in physics teaching laboratories. This pattern is due to the diffraction of the light waves. Now, by 1925, it was quite easy to get a stream of electrons. J. J. Thomson had done it in the 1890s when he discovered the electron. In 1926 his son, G. P. Thomson, tried the effect of shooting a beam of electrons through a thin gold foil – and got a diffraction pattern! Like his father, he was awarded a Nobel Prize (in 1937, shared with Dr C. J. Davisson from the USA who had carried out a similar experiment at the same time, with the same result).

So, not only had light a particle aspect, but electrons had a wave aspect. This idea of de Broglie catalysed the development of quantum mechanics. In 1925, Erwin Schrödinger used de Broglie’s idea to write his famous equation and produced an